TRANSIENT EDDIES IN THE MARS ATMOSPHERE: TWO REGIMES

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Introduction: One of the greatest surprises of the MGS TES thermal observations of the Mars atmosphere was the presence of large-amplitude transient eddies at "upper levels" in the northern hemisphere during periods following the onset of large dust storms in the autumn and winter seasons. These eddies were dominated by zonal wavenumber 1, and during some intervals they were observed to exhibit very long periods: as long as ~ 15-30 sols. No theoretical or modeling studies had predicted the existence of these transient eddies, though some work had hinted at it. We do not currently have a detailed dynamical understanding of these upper-level wave 1 transient eddies, but we now know that they dominate the middle and high latitude flow in the northern hemisphere when the wintertime atmosphere becomes sufficiently dusty. No comparable transient eddies have been observed during the southern winter seasons, although the southern eddies do have a more upper-level character during the so-called "solsticial pause" period surrounding southern winter solstice. The primary purpose of this paper is to examine what we know and what we do not know or understand about the circulation "regime changes" that occur in northern wintertime in association with large dust storm events. The upper-level transient eddy regime that we are particularly interested in is very much a part of the solsticial pause phenomenon in the northern hemisphere (Lewis et al., 2016), but our primary focus here is on the triggering of this regime by large regional and global dust storms.

Observations: It is a virtual certainty in hindsight that the two Viking landers observed at least one wintertime interval in the north that was dominated by upper-level transient eddies. This was the extended period following the onset of the very large global dust storm that began close to winter solstice in MY12 (the first Viking Mars year). As can be seen in Fig. 1, the meteorological variations observed at the two landing sites decreased dramatically in amplitude during this period. [The amplitudes of the pressure variations at the VL2 site decreased to values characteristic of the typical amplitudes observed at the subtropical VL1 site – roughly a factor of 10 smaller than typical amplitudes at VL2.] The periods of the variations also increased significantly from what they were prior to the onset of the global dust storm (Barnes, 1980).

After about 50 sols the amplitudes of the transient eddies at VL2 and VL1 began to gradually increase once again, on the way to a late winter and very early spring interval marked by the largest transient eddy amplitudes observed in MY12. It was speculated (e.g., Barnes, 1980) that the sharp decrease in the transient eddy amplitudes at VL2 and VL1 was caused by a substantial northward shift of the transient eddies. Such a shift was expected as a consequence of the expansion of the Hadley cell under highly dusty conditions. We now know that the dramatic reduction in the amplitudes of the transient eddies at the Viking lander sites must have been primarily due to an intrinsic reduction in the eddy amplitudes near the ground. Accompanying this there must have been a very large increase in the amplitudes of the transient eddies at upper levels in the atmosphere. The TES and MCS thermal observations have since shown us that the upper-level transient eddy activity can amplify enormously following the onset of both global and large regional dust storms in the northern wintertime seasons.

The first large dust storm event that was observed by TES after MGS began observing in its mapping orbit occurred in early autumn in MY24. Using all of the available TES and MCS observations, Kass et al. (2016) have classified the large regional dust storms that occur in northern autumn and winter into three basic types, denoted simply by A, B, and C. The storm observed by TES in mid-autumn in MY24 was the "A" storm for that year. The A storm has now been observed by TES and MCS to occur in every Mars year without a global dust storm (and in one with a global storm). In MY24 the A storm was well underway by L_s ~ 230. Fig. 2 (from Kass et al., 2016) shows upper level (0.5 mb) TES and MCS temperature data for all of the available non-global dust storm Mars years. Wilson et al. (2002) analyzed the TES data and showed that the period from L_s ~ 237-270 was marked by the presence of a large-amplitude upper level disturbance. This disturbance had a primarily zonal wavenumber 1 structure, exhibited maximum amplitudes at ~ 60-65N, and was propagating very slowly to the east (with a period of ~ 15-25 sols). Fig. 3, from Wilson et al. (2002), shows the behavior of this disturbance over time, at the 0.5 mb level and 62.5 N. At L_s ~ 270, the amplitude of the disturbance had largely diminished, and it was replaced by a different wave 1 disturbance having a much shorter period of ~ 6-8 sols, and a considerably smaller amplitude (see Fig. 3). Fig. 4 shows the amplitude structure of the very slowly propagating wave 1 disturbance in the latitude-height plane. It can be seen that the thermal amplitudes near the surface are quite small compared to those at higher levels. The smallness of these amplitudes demands that the surface pressure amplitudes of the disturbance must be relatively small.

In MY25 a very strong global dust storm event began near L_s ~ 184 and continued for a very considerable period of time. By L_s ~ 220-225 or so, TES observations revealed the presence of a very large-amplitude wave 1 disturbance, which was very slowly propagating (with a period similar to the upper-level disturbance in the autumn of MY24) towards the east. Very strong transient eddy activity at upper levels continued in MY25 well beyond northern winter solstice – until after L_s ~ 300. The fact that the large-amplitude wave 1 disturbance at upper levels did not become prominent for some time after the onset of the global dust storm is highly significant in the context of the factors that gave rise to it. The atmospheric mean state must not have been conducive to the existence of such an eddy disturbance until the autumn season had advanced sufficiently, even though it was already extremely dusty.

In MY26 both the A and C (mid-winter, see Fig. 2) regional dust storm events were relatively strong ones and large-amplitude upper level wave 1 disturbances were found to be present in the TES data following the onset of both storms. In the case of the C storm, which began at L_s ~ 315, the upper level disturbances did not persist for nearly as long as they had been observed to following the A storms in MY24 and MY26. This indicates that the "seasonal window" in which such disturbances can exist with large amplitudes probably does not extend into the late winter season.

Strong A and C regional dust storms and one global dust storm (in MY28) have been observed by MCS, and we are currently pursuing some analyses of the data for these events. Results from these analyses will be presented and discussed when this paper is given. Some simplified analyses have previously been performed, showing that large-amplitude upper level disturbances are present in the MCS data (D. Kass and J. Wilson, personal communications). Haberle et al. (2017) have very recently discovered that northern hemisphere wintertime transient eddy activity can be identified in the pressure data obtained by REMS on the Curiosity Rover in Gale Crater. Perhaps the strongest signal having a dominant period in the range of the transient eddies is one characterized by a period of ~ 16-17 sols during autumn in MY32. The duration of this long period pressure variation corresponds very closely to that which would be expected if it were associated with the very strong A dust storm that occurred in MY32 (L_s ~ 225-270, see Fig. 2). It is thus a real possibility that this signal is associated with a large-amplitude wave 1 disturbance at upper levels. Analysis of MCS temperature data for this interval in MY32 may be able to shed some light on this question.

Modeling: Surprisingly little work has been done to try to model the very large-amplitude upper level wave 1 disturbances observed by TES and MCS. Achieving some sort of basic dynamical understanding of these disturbances is an obvious goal for such modeling. Given that they are present during certain wintertime seasons when the atmospheric dustiness is high enough, and that they constitute a very basic change in the primary character of the wintertime transient eddies, a full understanding would certainly also include the nature of the "regime change" process that occurs in the northern hemisphere wintertime atmosphere. The transient eddy activity that exists prior to the emergence of the wave 1 upper-level disturbances is essentially consistent with baroclinic instability that is dynamically tied to the existence of strong surface thermal gradients. These transient eddies have substantial temperature amplitudes near the surface, and thus also substantial surface pressure amplitudes. Transient eddy activity dominated by zonal wavenumber 3 disturbances is very often present prior to the development of both the A and C regional dust storms (Hinson et al., 2012). Such eddy activity is particularly capable of raising dust, often in association with "flushing" dust storms that can cross the equator (e.g., Wang, 2007). Some of the flushing storms, in fact, act to directly trigger some of the A and C regional storms. The wave 3 transient eddies have the shallowest vertical structures, with the wave 2 and wave 1 structures being considerably deeper. The very long period wave 1 upper-level transient eddies have the deepest structures of all, having only small near-surface amplitudes. During the seasonal intervals when these eddies are dominant, the much shallower transient eddy activity is greatly reduced. The transient eddy regime changes rather dramatically, from one dominated by disturbances with large amplitudes near the surface to one dominated by eddies with much smaller amplitudes close to the ground. Dust storms associated with transient eddy activity simply do not occur during the northern wintertime seasonal periods when the upper-level transient eddies are dominant (Wang, 2007).

Wilson et al. (2002) performed GCM simulations to try to simulate the TES observations of the MY24 mid-autumn (A) dust storm. They were able to simulate wave 1 transient eddies that bore considerable resemblance to those in the TES data. Their simulation for the L_s ~ 230-270 period produced a wave 1 disturbance having a ~ 10 sol period. For the seasonal interval after winter solstice their simulation produced a ~ 6-8 sol disturbance that strongly resembled disturbances having this same period in other GCM simulations performed previously. It also closely resembled transient eddy modes having this period in the TES data, for non-dust storm periods.

The slow deep wave 1 mode (with a 10 sol period) in the simulations in Wilson et al. (2002) had a highly barotropic vertical structure – as do the upper-level wave 1 eddies in the TES data. The wind amplitudes exhibited maximum values well above the 0.5 mb level, and these had a very broad structure in latitude at upper levels. The eddy momentum fluxes at upper levels were very large, and were such as to extract eddy kinetic energy from the kinetic energy of the zonal-mean flow. Upper-level baroclinic energy conversions were also present in the model. Thus the energetics of the slow deep wave 1 disturbance were very different than those of the normal transient eddies found in various GCM simulations. Wilson et al. (2002) argued that the slow deep wave 1 disturbance had some of the characteristics of a Rossy wave free mode in middle and high latitudes, and that it appeared to be dynamically linked to inertially unstable regions in low latitudes produced by the intense Hadley circulation under very dusty conditions (as previously discussed by Barnes and Haberle, 1996).

Previous modeling work had actually pointed to the existence of stationary or very slowly propagating wave 1 free modes in northern wintertime. In particular, Hollingsworth and Barnes (1996) had carried out a linear modeling study of forced stationary waves in the Mars atmosphere. Finding that very large wave 1 amplitudes could be obtained in the model with a basic state intended to represent dusty wintertime conditions, they performed a free mode "search" with the model. This simply involved applying a simple forcing for wave 1, and sweeping through all model frequencies – corresponding to both eastward and westward traveling waves. Fig. 6 shows the results from this set of calculations with the linear model. It can be seen that the wave 1 amplitudes obtained for the dusty basic state are much greater than those for the relatively non-dusty wintertime state, at frequencies closely surrounding the stationary (zero) frequency. The response looks very much like what one expects for resonance in a system with quite strong dissipation.

There is an additional aspect of the observed slow deep wave 1 disturbances that indicates that they may be associated with atmospheric conditions that are near resonance for stationary forcing. This is the fact that in the very early stages of the development of the slow deep wave 1 disturbance, there is a large-amplitude stationary wave 1 disturbance that exhibits a sudden change in phase of almost 180 degrees. This behavior can be clearly seen in Fig. 3, between L_s ~ 228-238. There are several other examples of this same behavior in the TES data. This is consistent with what one expects, on the basis of simple modeling and theory, if a stationary or near-stationary wave 1 changes from being vertically propagating to being vertical trapped. It is at least plausible that this could occur in the Mars atmosphere in association with a large dust storm, as shown in the context of a simple linear model by Barnes et al. (1996).

We have begun to perform GCM simulations for dusty wintertime conditions and carry out analyses of the results to see if slow deep wave one disturbances like those in the observations are present in the model circulation. It certainly should be possible to simulate such disturbances and then perform detailed analyses and further modeling to gain an understanding of their dynamics. We are hopeful that we will be able to present and discuss some of the results from this modeling work.

Summary: In the northern hemisphere of Mars, two very different transient eddy regimes exist. In the normal regime the transient eddies have structures that are consistent with "normal" baroclinic instability that is dependent upon the existence of strong surface thermal gradients. These eddies have large amplitudes near the surface, and can act to raise considerable amounts of dust. Wavenumber 3 eddies are particularly important in triggering dust storm events, especially the flushing storms that can cross the equator. The alternate transient eddy regime is one which is dominated by very deep eddies that have large amplitudes at upper levels and relatively small amplitudes near the ground. This regime develops quickly following the onset of large regional dust storms: the A and C storms, as defined by Kass et al. (2016). The upper level regime also develops very strongly after the onset of global dust storms.

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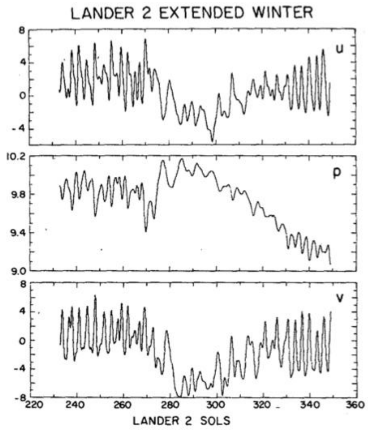

Fig. 1: Low-pass filtered pressure and wind data at VL2 during the MY12 winter solstice global dust storm. From Barnes (1980).

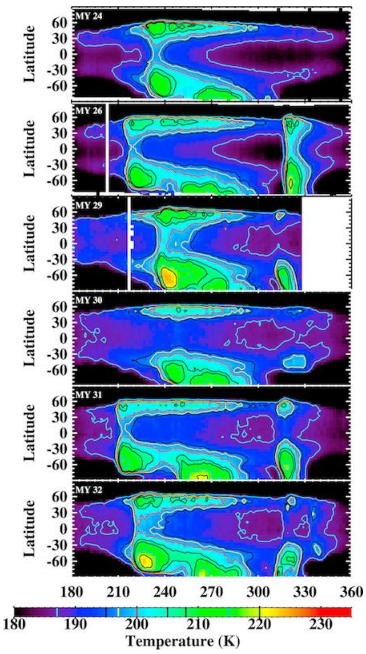

Fig. 2: Images showing large regional dust storm activity in TES and MCS Mars years without a global dust storm. From Kass et al. (2016).

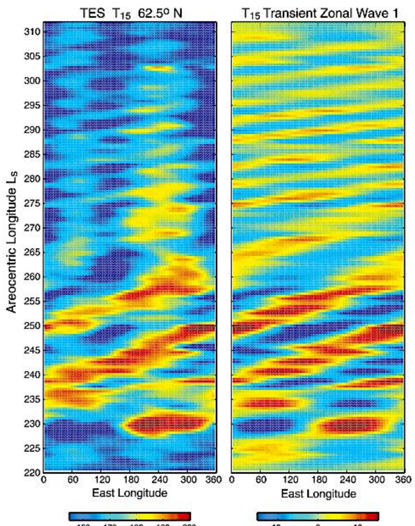

Fig. 3: Longitude-time plots of the eddy temperature field as observed by TES at ~ 0.5 mb and 62.5N in MY24. From Wilson et al. (2002).

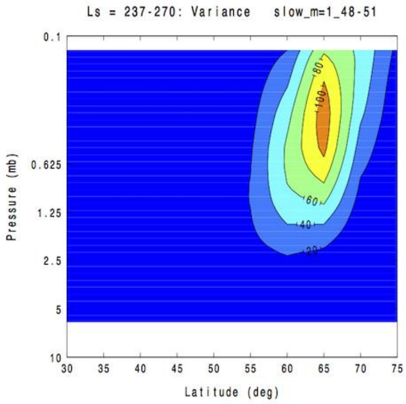

Fig. 4: Temperature variance (K^2) of the slow deep wave 1 disturbance for the L_s ~ 237-270 period in MY24.

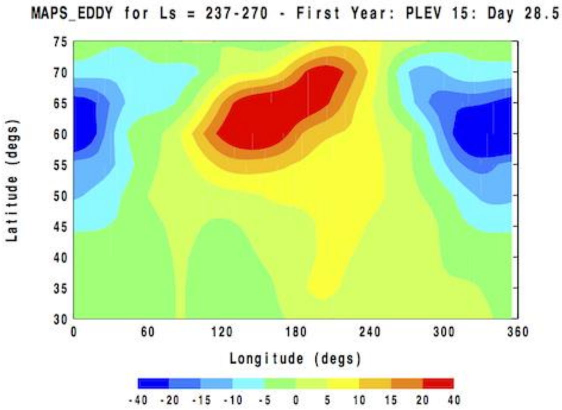

Fig. 5: A synoptic transient eddy map at 0.5 mb, produced from an FFSM analysis of TES temperature data, for the same dust storm period as in Fig. 3.

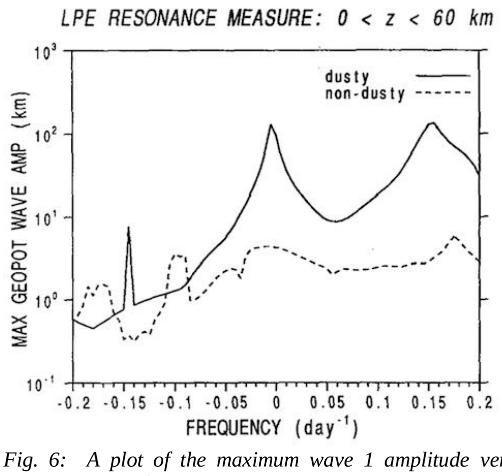

Fig. 6: A plot of the maximum wave 1 amplitude versus frequency derived from calculations with a linear primitive equation model for two different basic states. The strong dissipation in each case is the same. From Hollingsworth and Barnes (1996).